The shift from film to digital product: focus on CORONA imagery.

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Summary: This paper discusses the issue of the shift of USGS (United States Geological Survey) in providing a digital instead of a film product for the declassified imagery. The paper focuses on CORONA imagery. With the advent of computers and subsequently the increase of processing power, the sciences of photogrammetry and remote sensing and their respective approaches have evolved into a more interdisciplinary network within which GIS (Geographical Information Science) was a catalyst. The sensor technologies similarly evolved, and the paper discusses potential and trade-offs of this evolution. Applications showed that it is up to the user to select the most appropriate approach and media so as to meet the application's needs.

1. Introduction

On 3rd of September 2004, USGS decided to stop providing photographic products to the public[1]. Instead, digital products will be produced and provided. Once the film is digitised, most of it will continue to be stored in the USGS facilities. Film with vinegar syndrome will be sent to NARA (National Archives Record Administration) to be placed in frozen storage.

The decision of USGS to cease operations in the creation of photographic products raised once again the issue of whether the modern photogrammetric scanners can capture the full film quality or not, and whether it is better to extract information from film or from digital product.

This paper is comparing the two products with main focus on declassified imagery, in particular the film product of KH-4B (KH for KeyHole) satellite design of the CORONA program. However, the discussion can be accommodated in other photographic products and applications too.

LEACHTENAUER *et al.* (1997) did the first research on the problem of how to best use the CORONA product. After experiments with KH-4A film product, they concluded that for lossless digitizing, a 4 μm digitizing spot size is required. However, as GALIATSATOS (2004) proved, the CORONA program had a variety of films, lens, filters, and cameras. This variety resulted in different image quality even between cameras of the same mission. LEACHTENAUER *et al.* (1997) did not discuss on other ways of using the film, on the film properties (e.g. density, sensitivity), or the film quality itself. This paper aims to continue the work of LEACHTENAUER *et al.* (1997) through developing on the not-fully developed issues.

The discussion will be application-oriented with main focus on current trends and existing work.

In the following sections, first a brief historical summary of the CORONA imagery is presented. The main characteristics of the film and the filters are then illustrated as they were found in the declassified documentation. A brief history follows regarding the transfer from photointerpretation to image analysis and the eventual complementary role of the methods regardless of the media (film or digital). The transfer from film to CCD sensors is then discussed and the trade-offs are briefly presented. Finally, the focus goes back to CORONA and particular applications with all the issues that were met.

2. CORONA imagery

CORONA was a program designed to support U.S. Intelligence between 1958 and 1972. It officially started with a formal endorsement by President Dwight E. Eisenhower on 8th February 1958. (HALL, 1997). The launch operations began on 25th June 1959. On 10th August 1960, the diagnostic mission was

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[1] http://edc.usgs.gov/USGStostopPhotographicProduction.html (last accessed: December 2008)

successful, and 2 days later, on 12th August, the capsule for the film was "recovered undamaged". After eight failures in photoreconnaissance, the first successful mission occurred on 18th August 1960 when the first CORONA image of an intelligence target was acquired during Mission 9009 (McDONALD, 1995).

The camera carried on that Mission would be retrospectively designated the KH-1. The next successful CORONA Mission would be conducted on 7th December 1960. This time a more advanced camera system, the KH-2, was on board. From that time, through to the end of the CORONA program in 1972, there was a succession of new camera systems – the KH-3, KH-4, KH-4A and KH-4B (RICHELSON, 1999). In the end, CORONA acquired over 800,000 frames of photographs with a total coverage of at least 600 to 750 million nmi^2 (square nautical miles) of the Earth's surface. On 22nd February 1995, President Clinton signed the Executive Order 12951 that declassified those images (CLINTON, 1995a). Furthermore, the President delegated any future declassification approval to the Director of Defence and State. However, the Executive Order 12951 addresses only the imagery declassification. Other declassification (e.g. CORONA reports) falls under Executive Order 12958 (17th April 1995) (CLINTON, 1995b). The latter was amended by executive order 13292 (25th March 2003) (BUSH, 2003).

Table 1 summarises the major developments in the CORONA satellite programme. The main differences lay in the improvement of the lens, the creation of tougher and finer film, the boost capacity of the rocket, the better control of vehicle stability, and last but not least, the freedom to innovate and to redesign the satellite from scratch. It must be noted that improvements were incorporated into every mission.

Tab. 1 - Major operational and construction difference among CORONA designs

	KH-1	KH-2	KH-3	KH-4	KH-4A	KH-4B
Period of operation	27/6/59-13/9/60	26/10/60-23/10/61	30/8/61-13/1/62	27/2/62-24/3/64	24/8/63-22/9/69	15/9/67-25/5/72
Amount of frames	1432	7246	9918	101743	517688	188526
Mission life (days)	1	2-3	1-4	6-7	4-15	19
Altitude (km)						
Lower (estimated)	192	252	217	211	180	150
Higher (estimated)	817	704	232	415	n/a	n/a
Successful missions	1	3	5	20	49	16
Targets	USSR	Emphasis on USSR		Worldwide/emphasis on denied areas		
Aperture width	5.265°	5.265°	5.265°	5.265°	5.265°	5.265°
Pan angle	71.16°	71.16°	71.16°	71.16°	71.16°	71.16°
Lens	F/5.0 Tessar	F/5.0 Tessar	F/3.5 Petzval	F/3.5 Petzval	F/3.5 Petzval	F/3.5 Petzval
Focal length (cm)	61	61	61	61	61	61
Resolution						
Ground (m)	12.20	7.60	3.70-7.60	3.00-7.60	2.70-7.60	1.80-7.60
Film (lp/mm)	50-100	50-100	50-100	50-100	120	160
Nominal ground coverage per image frame	15.3x209 to 42x579 (km)	15.3x209 to 42x579 (km)	15.3x209 to 42x579 (km)	15.3x209 to 42x579 (km)	17x232 (km)	13.8x188 (km)
Nominal photoscale in film	1:275,000 to 1:760,000	1:275,000 to 1:760,000	1:275,000 to 1:760,000	1:300,000	1:305,000	1:247,500

All the values in table 1 are nominal. For precise values in every mission, the reader should consult the original NRO and NARA reports (GALIATSATOS, 2004). Table 1 was made based on information from MCDONALD (1997), MADDEN (1996), DAY *et al.* (1998), and PEEBLES (1997).

Some of the nominal values of the table 1 are very general and only roughly represent the real values. In this paper we shall focus on the parameters that are relevant to the image quality.

Various factors affect the resolution of the panoramic cameras: the resolution capacity of the optics (Petzval lens), the resolution capacity of the film, the focus condition of the lens, the exposure and development of the film, and the blur which results from the motion of the aerial image across the film during exposure (NRO, 1967). There are many ways to determine what resolution is.

The Itek engineers were aware of the effect that the angle of the camera with the target and the sun may have to the image quality. For this reason, they were using different camera systems (film, filter) depending on the viewing angle of the camera and the direction of the platform. In more advanced systems, the filter was changing depending on the orbit (ascending / descending), the latitude of the target and the solar altitude. During the CORONA program, constantly all involved companies (e.g. Itek, Kodak) were experimenting with every mission.

The main purpose during operations in the 1960s was to increase the performance of the photointerpretation. As we read in NRO (1967), the focus was on improving the microcontrast, that is the contrast when in high magnification. Thus, the photointerpreter was able to identify small details in the image.

3. Film photographic properties

Characteristic curve

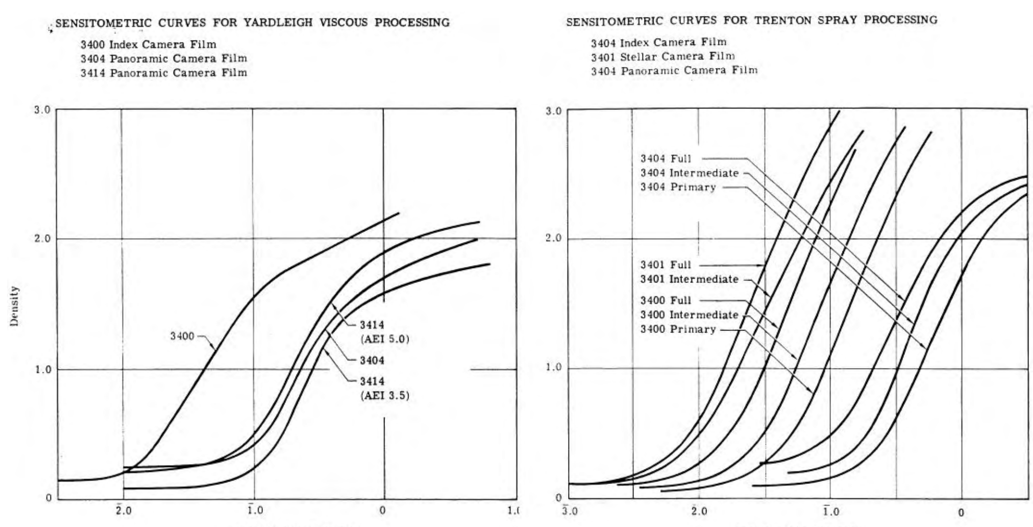

Fig. 1 - Sensitometric curves for two different processing methods (NRO, 1970).

According to NRO (1970), during the earliest missions, the CORONA project used variable spray processing conditions for 3404 film. This included a three-level processing – primary, intermediate and full (which provided different sensitometric responses). Beginning with mission 1104 (7 August 1968), a single level yardleigh viscous process was used (fig.1). On July 1970 Eastman Kodak replaced film 3404 with film 3414. According to NRO (1970), the 3414 emulsion characteristics are similar to 3404 emulsion with the exception of spectral response and film speed.

Spectral sensitivity

Figure 2 displays the spectral sensitivity of the films 3404 and 3414, along with the films used in index, horizon and stellar cameras. Notice the higher sensitivity of the films 3404 and 3414 in the red part of the spectrum and compare it with the filters that were used in the CORONA program.

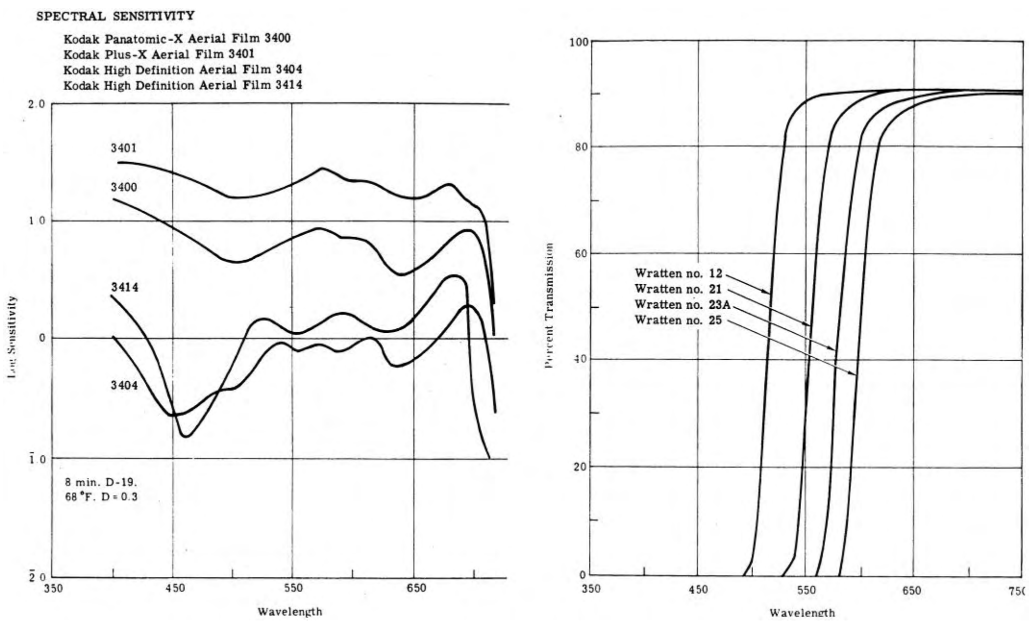

Fig. 2 - Spectral sensitivity curves of the CORONA films (left) and characteristic curves of CORONA filters (right) (NRO, 1970).

Dynamic Range

The definition of the dynamic range of the film is important for deciding the radiometric resolution of the scanning. Figure 3 displays the dynamic range of the 3404 film through the assumed acceptable minimum and maximum density points. This figure highlights the radiometric resolution of the film (1.5D), which empirically corresponds to a 7-bit radiometric resolution (McGlone, 2004).

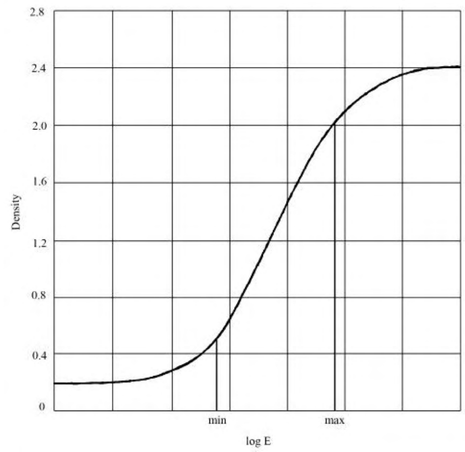

Fig. 3 - Assumed acceptable minimum and maximum density points for film 3404 (NRO, 1970).

Filters

Filters are required for most aerial reconnaissance systems in order to counteract the contrast reduction effects from the bluish haze light. The filters commonly employed in CORONA project are Wratten gelatine filters and are yellow to red in colour. Generally, the deeper red the filter, the greater the haze cutting ability, and the higher the contrast. However, the redder the filter, the higher the filter factor which in turn makes longer exposure times necessary. Apart from Wratten filters, there were experiments with colour correction and polarising filters in various missions. Because gelatine filters were drying out in the vacuum of space, glass filters were used with the same thickness as gelatine filters. Figure 2 displays the different filters that were applied during the CORONA program.

4. Evolution of sciences

Photography existed long before satellite observation. L.J.M. Daguerre and J.N. Niepce developed the first commonly used form of photograph between 1835 and 1839. In 1845, the first panoramic photograph was taken, and in 1849 an exhaustive program started to prove that photography could be used for the creation of topographic maps. The same year, the first stereo-photography is produced. In 1858, Gaspard Felix Tournachon took the first known photographs from an overhead platform, a balloon (PHILIPSON, 1997). For the next 101 years, aerial photography was developed and widely used in military and civilian applications. The platforms changed to include kites, pigeons, balloons and airplanes (chapter 2 in REEVES, 1975). The era of satellite photogrammetry (Slama *et al.*, 1980) starts in 1960 with the CORONA military reconnaissance program. The era of using satellite images for mapping and making measurements starts in 1962 with the CORONA KH-4 satellite design.
COLWELL (1960) defined photographic interpretation (also termed photointerpretation) as

> *"the process by which humans examine photographic images for the purpose of identifying objects and judging their significance"*

With the advent of computer technology, the methods for photographic interpretation changed and the new term *image analysis* (also termed *quantitative analysis*) came to complement (underlined) the old term:

"Image analysis is the process by which humans <u>and/or machines</u> examine photographic images <u>and/or digital data</u> for the purpose of identifying objects and judging their significance" (PHILIPSON, 1997)

Photointerpretation involves direct human interaction, and thus it is good for spatial assessment but not for quantitative accuracy. By contrast, image analysis requires little human interaction and it is mainly based on machine computational capability, and thus it has high quantitative accuracy but low spatial assessment capability.
Today, both techniques are used in very specific and complementary ways, and the approaches have their own roles. On one hand, if digital image processing is applied beforehand to enhance the imagery, then this helps the photointerpreter in his work. On the other hand, image analysis depends on information provided at key stages by an analyst, who is often using photointerpretation (RICHARDS & JIA, 1999).
KONECNY (2003) defines *remote sensing* and *photogrammetry* according to their object of study:

"Photogrammetry concerns itself with the geometric measurement of objects in analogue or digital images"

"Remote sensing can be considered as the identification of objects by indirect means using naturally existing or artificially created force fields".

Thus, photogrammetric techniques were adopted by remote sensing mainly for quantitative analysis. In its turn, remote sensing expanded the data that could aid an image analyst with the extraction of quantitative information.
All of the above terms give a specific meaning to the approaches, but the approaches complement each other when it comes into implementation. In other words, the sciences of photogrammetry and remote sensing moved from the previous independent way of working, towards a more interdisciplinary network, where in comparison with other sciences like GIS, Geodesy, and Cartography, they produce better results and increase the processing capability for modern day applications (fig. 4).

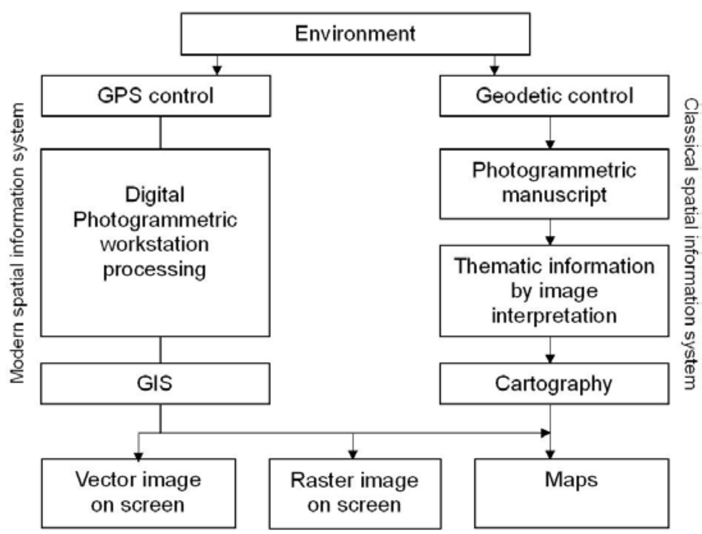

Fig. 4 - Classical and modern geospatial information system (reproduced from KONECNY, 2003)

5. Evolution of technology

The interdisciplinary approach has been encouraged by developments in computer technology, especially Geographical Information Systems. In the past, the main product was film or photographic print recorded at visible wavelengths (some special colour films were sensitive in IR light too). The distance of cameras from the Earth's surface and the need for high ground resolution (especially for military reconnaissance programs) demanded a sufficiently high resolution film. This led to the production of films with 160 lp/mm resolution (CORONA program), 320 lp/mm (GAMBIT program), and higher. Even with today's technology, such resolutions cannot be transferred to digital format for computer processing without loss of data and interpretability. During that era, the best approach was photointerpretation alone, since the computers were not powerful enough to read and analyse such huge amount of data. Thus, with the use of large light-tables and magnifiers, the film was analysed by the most advanced computer in existence, the human brain.

In 1970, W. Boyle and G. Smith of Bell Labs discovered the CCD (Charged Coupled Device) (BOYLE & SMITH, 1970). CCD is an imaging electro-optical sensor. It can record radiation from a ground resolution element for representation within a pixel in an image. The simplest CCD array is linear (REES, 1999). Later, the CCD was improved and it became the dominant process for image capture. Although other devices became available (e.g. CMOS, Complementary Metal Oxide Semiconductor), the CCD gives the best performance in terms of resolution, sensitivity, and other parameters, with the exception of cost. FELBER (2002) provides a very good summary of the development, structure and operation of CCDs.

The product of CCD image capture is a matrix of digital picture elements (pixels). It can be attached to detectors that are sensible to a wide range of wavelengths. It is sensitive to the visible, near-infrared, near-ultraviolet, thermal and microwave parts of the electromagnetic spectrum. On the contrary, film is limited to available film emulsions and spectral characteristics.

When comparing film with the CCD in photogrammetry and remote sensing applications, the former has the advantages of finer resolution, rigorous geometry and being a mature technology (established reliability of performance, with support and systems existing worldwide). But the processing of the film itself introduces distortions that are nearly impossible to model (treatment during film development, film must be scanned).

The product of CCD image capture may be derived from CCD matrices or CCD linear arrays. Depending on the product, the user has to apply different techniques for the optimum gain of qualitative and/or quantitative information. Always, the user must know as much as possible about the product's background. Further processing mainly depends on the aims and objectives and the tools used to aid the process.

The CCD matrices share the same conical geometry with film cameras. The resolution is coarser, but there is rigorous geometry with better precision and fewer distortions when compared to film (KASSER, 2002a).

On the other hand, the CCD linear arrays have cylindro-conical geometry. This type of geometry is found on most of today's satellite sensors (Landsat, IKONOS, SPOT, etc.), even though not all of them use CCDs (Landsat) (KASSER, 2002b). This geometry implies new digital data process approaches, which forbid the use of standard software of classic photogrammetric stations (KASSER, 2002a).

TORLEGARD (1992) wrote that the aerial film camera would be the main sensing system for map production and revision in large- and medium-scale cartography for the next several years. LIGHT (1996) presents a list of tradeoffs between CCD and film sensors, and Fricker *et al.* (1999) identify practical difficulties for the transition from film to digital. Today, one would agree that the high resolution space systems and the CCD sensors have improved significantly and are already replacing film cameras in most applications.

The airborne imagery cannot be replaced mainly because of limitations in the use of spaceborne sensors (Fricker, 2005). For this reason, in the recent years there has been development of airborne digital sensors such as Leica ADS80 (Airborne Digital Sensor), Microsoft UltraCam*X*™, and Integraph Z/I Imaging® DMC® (Digital Mapping Camera) systems. Recent improvements in the automation and quality of the sensors (Jacobsen, 2007) have resulted in an increase of commercially available digital systems.

6. Focus on applications

TAPPAN *et al.* (2000) preferred to photointerpret CORONA straight from the film without any digitizing. This is a rigorous approach but it inhibits the GIS potential of data integration. BINDSCHADLER & VORNBERGER (1998) scanned the film to a satisfactory scale for their application, while PALMER (2002) preferred to create large scale photographic prints and then process these on a flatbed scanner. Palmer's approach is simple but effective and demonstrates that for certain applications complex data pre-processing may not be necessary.

From the above, it is necessary to mention that the way CORONA will be prepared depends heavily on the needs of the application and the expertise of the people using it. This means that no matter how well the CORONA film is scanned at the USGS facilities, the final digital product can be a major burden for people who do not have the relevant expertise or computing power to handle it.

As GALIATSATOS (2004) concludes, the use of photogrammetric scanner for the scanning of the CORONA film is probably the best solution for the creation of digital product. The main reasons are the capability to scan at high resolution without interpolation, and the resulting digital files are geometrically corrected. The latter is achieved by the use of specific algorithms that reproduce the correction model of the scanner's errors. USGS is using photogrammetric scanner (Leica DSW700), and the film is scanned to the highest optical resolution of the scanner (7 μm), where the scanner utilises a Schneider 120mm, f/5.6, colour-corrected lens. The radiometric uniformity is calibrated monthly and the geometric accuracy is calibrated periodically through the year (there is an effort to do it monthly) and is less than 2 micron (Borchardt, 2005; 2009, personal communication).

As LEACHTENAUER *et al.* (1997) showed the 4 μm would be the ideal scanning resolution so as to scan the film without any loss of information. This is a good reason for people to insist on using the film. On the other hand, is it really important this difference in resolution for the majority of applications?

THOM (2002) shows that the smaller the step of scan, the better will be the precision and the spatial resolution, but there may also be loss of radiometric precision. In practical applications, the impact of radiometric quality on the geometric precision is not easy to evaluate. Generally, weakly contrasted details can be separated when attention has been given to the radiometric quality. The USGS digital product of CORONA imagery shows that the majority of the radiometric values represented on the film are captured. From the film density range we gather that the film is roughly 7-bit and empirically we need to scan two bits more so as to capture the full range. The USGS digital product is 8-bit, still more than the assumed density range of the film, however not as much as experience dictates. In most applications though, this is a negligible difference.

GALIATSATOS *et al.* (2008) identified a distortion in the texture of the imagery after they discovered the result of it in the extracted DEM. They used Vexcel VX4000 which is a matrix (or area) scanner. KASSER (2002c) points out that even if a calibration is applied to the scanner, some irregularities may persist. For example, calibration errors or dust particles will affect the radiometric precision of the scanning. In particular for matrix CCD scanners, there will be periodic and annoying artefacts due to repetition of errors according to a regular paving, and of radiometric discontinuities between successive positions of the matrix. Baltsavias (1999) mentions that there may be radiometric differences along the seam lines of the partial scans of the matrix.

The DSW700 is a matrix scanner too, and a similar texture distortion of smaller extent was detected (STICHELBAUT, 2008, personal communication) by the research team that is working in the Altai region of Siberia (GHEYLE *et al.*, 2004). This is an issue that has not been resolved yet. Jacobsen and Gaffga (1998) demonstrate the issue of image quality deterioration during scanning. Other problems that were identified in the USGS digital product were Newton rings and dust particles.

7. Conclusions

As the world evolves, things change. Some time ago photogrammetry and remote sensing communities worked independently, and the digitising of the film was technically impossible. Nowadays, the sciences have approached and complement each other in an interdisciplinary way. Similarly, the processing power of modern personal computers allows the digital analysis of large amounts of data. So, the transfer of media from the film to the digital is an inevitable result of the world's evolution, similar to the transfer from the papyrus to the codex, and the from the codex to the book.

The digitising is not perfect, even if the professional photogrammetric scanners are used. It may not capture the full information included in the film and some errors may be incorporated in the effort to get as much information as possible, especially if care is not taken with regard to radiometric precision.

Ultimately, it depends on the application needs, and most applications do not require more than what the photogrammetric scanners can offer. Some applications actually used photographic printing techniques and flatbed scanners, and even though these techniques did not capture the full potential of CORONA imagery, they still provided useful results.

In summary, the USGS digital product is not a perfect representation of the information content of the film. However, it captures the greatest amount of the information content within the limits of the available technology. The final image file may be large but modern technology can handle it without much trouble. It is the user who should be aware of the product's background (e.g. scanning artefacts, film characteristics) and should have the expertise to utilise the full potential of the acquired image information in a GIS environment.

On the other hand, the film duplication process is not perfect either, as the printer introduced a slight stretch in the Y-axis (Happell, 2000, personal communication). The technology to directly process the particular film frame is difficult to find today, as it only existed within the intelligence community. Again, it depends on the user's expertise as to how the film will be processed. For this, the film offers more freedom to the user to select an approach for the application. However, if it is not digitised then any potential use of GIS is inhibited.

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